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Estimating the potential for twenty-first century sudden climate change

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I investigate the potential for sudden climate change during the current century. This investigation takes into account evidence from the Earth's history, from climate models and our understanding of the physical processes governing climate shifts. Sudden alterations to climate forcing seem to be improbable, with sudden changes instead most likely to arise from climate feedbacks. Based on projections from models validated against historical events, dramatic changes in ocean circulation appear unlikely. Ecosystem–climate feedbacks clearly have the potential to induce sudden change, but are relatively poorly understood at present. More probable sudden changes are large increases in the frequency of summer heatwaves and changes resulting from feedbacks involving hydrology. These include ice sheet decay, which may be set in motion this century. The most devastating consequences are likely to occur further in the future, however. Reductions in subtropical precipitation are likely to be the most severe hydrologic effects this century, with rapid changes due to the feedbacks of relatively well-understood large-scale circulation patterns. Water stress may become particularly acute in the Southwest US and Mexico, and in the Mediterranean and Middle East, where rainfall decreases of 10–25% (regionally) and up to 40% (locally) are projected.

Keywords: rapid climate change; water cycle; solar variability; ice sheets; abrupt climate change; sea-level rise

1. Introduction

It is important to estimate the likelihood of sudden climate change in the near future for many reasons. Most importantly, it enables early development of potential mitigation and adaptation strategies, allows for a better evaluation of risk exposure and provides a guide for climate monitoring that could aid early detection of the most disruptive changes. As such, the study of sudden climate change has received much attention (Broecker 1997; Crowley & North 1998; Taylor 1999; Clark *et al.* 2002), especially since the early 1990s when high-resolution ice core data from Greenland demonstrated that climate had changed rapidly on time scales shorter than a century in the past (Dansgaard *et al.* 1993; Grootes *et al.* 1993).

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One contribution of 9 to a Theme Issue 'Climate change and urban areas'.

Less quantifiably, near-future sudden climate change may also play a major role in the socio-political response to 'global warming'. Societal and governmental structures are typically geared towards time horizons of *ca* 5 years or less, and often have difficulty coping with changes taking place on longer time scales. Many aspects of global climate change appear to fall into this category, prompting analogies between human society and the behaviour of a frog that will immediately jump out if placed into scalding water, but will allow itself to be boiled alive if placed into cool water that is then gradually heated. It is worth noting the example of ozone depletion, a global environmental problem that was addressed effectively by the world community. Thinning of the stratospheric ozone layer caused widespread concern, but little action was taken for many years until the discovery of a massive springtime ozone hole over Antarctica in 1985. The sudden onset of this dramatic change prompted a rapid response, with the signing of the Montreal Protocol to control substances that deplete the ozone layer occurring only 2 years later. Thus, the appearance of a substantial, sudden climate shift might have important consequences for humanity's steps to address climate change in addition to the traditional impacts consisting of the effects on natural ecosystems, agriculture and other managed ecosystems, health, etc. While sudden climate changes typically have detrimental effects on ecosystems, which have evolved with the capacity to adapt to much slower changes, and on economic systems, which are optimized for the current climate state, there is an intriguing possibility that near-term sudden climate change could substantially affect the will to tackle climate change, and thus could greatly influence the likelihood of some of the most devastating, very long-term consequences of global warming coming to pass (e.g. catastrophic sea-level rise due to melting of the polar ice sheets).

An understanding of the potential for sudden climate change to take place during the coming century is difficult, however, owing to the complexity of the climate system and in many cases, the lack of appropriate historical analogues. Climate responds to changes in external factors that alter the Earth's energy balance with space. These factors, referred to as forcings, include volcanic eruptions, solar output changes, and greenhouse gas (GHG) and aerosol abundance changes. The effect of the initial forcing can be amplified or suppressed by the response of processes within the Earth's climate system, called feedbacks. The possibility of sudden climate change arises either from large rapid changes in the forcings or from the potential for feedbacks to be strong and perhaps nonlinear.

An assessment of the potential for near-term sudden climate change, defined here as within the next century, thus requires an estimate of how climate feedbacks will respond to the continued increase in GHGs projected to dominate twenty-first century climate forcing. We must rely on projections from climate models for such an estimate. However, we can only establish a reasonable degree of trust in the models by testing the simulations against available historical analogues. Thus, any evaluation of the possibility for sudden climate change must rest on a careful consideration of model results informed by palaeoclimate evidence for climate feedbacks and past changes.

Palaeoclimate records extending back more than half a million years show regular glacial cycles driven by the well-known variations in the Earth's orbit around the Sun (Siegenthaler *et al.* 2005). As the energy changes resulting from orbital forcing are quite small, the large response demonstrates that the Earth's climate is very sensitive to small forcings if given enough time to respond. The palaeoclimate data also show that typically warming takes place substantially faster than cooling. For glacial cycles, time scales for cooling are set by the rate at which ice sheets grow, while those for warming are set by ice sheet decay and by the response times for terrestrial and marine ecosystem feedbacks that amplify the orbital forcings via biogeochemical cycling of GHGs.

Variations can also take place at much shorter time scales than glacial–interglacial cycles. We may take some comfort from the fact that palaeoclimate data from ice cores and ocean sediments indicate that while climate during glacial periods tends to show frequent dramatic rapid changes, interglacial periods are in contrast comparatively stable (McManus *et al.* 2002). However, the current 'climate experiment' in which humans are pouring GHGs and aerosols into the atmosphere does not necessarily have a good analogue in Earth's history. For example, carbon dioxide and methane levels have increased by approximately 25 and 150%, respectively, since the pre-industrial era, each now reaching levels not seen in at least 650 000 years (Siegenthaler *et al.* 2005; Spahni *et al.* 2005). Both are projected to continue increasing substantially over the coming century, creating conditions that probably have not been experienced by the Earth since the continents came into their present configuration. Thus, it is not possible to infer from palaeoclimate data that the current interglacial will have as stable a climate as previous interglacial periods, or indeed that it will remain as stable as it has been during the current interglacial (the Holocene) thus far.

2. Sudden changes in climate forcing

Three types of large sudden changes in climate forcing are thought to have occurred in the past: explosive volcanism; asteroid impacts; and release of methane from hydrate deposits. While explosions such as the 'super-eruption' of Toba *ca* 75 000 years ago in modern-day Indonesia can dramatically affect climate, their timing is unpredictable. Similarly, asteroid impacts such as the one thought to have contributed to the extinction of the dinosaurs are also unpredictable. Based on palaeoclimate evidence, however, both super-eruptions and extraterrestrial impacts seem fortunately to be rather rare, and thus are an unlikely candidate for near-term sudden climate change.

The other dramatic change in climate forcing with historical precedent, methane hydrate release, is also difficult to predict. The primary example from the Earth's history is a release that has been implicated in substantial warming at the beginning of the Eocene period *ca* 55 Myr ago. During this period, the release of methane from hydrate deposits on the continental slope is believed to have led to greenhouse warming of approximately 5–7°C at high latitudes (Bains *et al.* 1999; Katz *et al.* 1999). This provides strong evidence that a sudden massive release of methane from hydrates can take place and affect climate. However, evidence from the more recent past suggests that hydrates have been quite stable during the last glacial and the present interglacial (together *ca* 100 000 years), even during sizeable climate perturbations such as the Younger Dryas (YD) period (Sowers 2006), suggesting that release requires a relatively rare set of conditions. Gauging the probability of massive release in the near-future is challenging, as two competing influences are at work. These are the effects of increasing pressure as the oceans gain water, which reduces the likelihood of release, and increasing temperature in the ocean's bottom waters, which could penetrate the sea floor, warm the hydrates and increasing the chances of release. With little palaeoclimate evidence from the last several million years against which to calibrate such estimates, it is difficult to establish the credibility of hydrate release models. Thus, as with volcanoes and asteroids, the rarity of palaeoclimate evidence for hydrate-induced climate changes argues that this is a fairly unlikely candidate for near-term sudden climate change. Unlike the others, however, anthropogenic climate change may alter the probability of hydrate release when compared with the past, making the overall probability of near-term release extremely difficult to estimate.

It thus appears that the likelihood of an abrupt change in natural climate forcings is relatively small. From a geological perspective, however, the anthropogenic increases in GHGs discussed earlier are certainly rapid. The most probable sources of sudden climate change are thus phenomena with large responses to anthropogenic GHG forcing. We now consider several of these in turn.

3. Ocean circulation changes

Among climate feedbacks with the potential to cause sudden climate change, the response of ocean circulation to climate change may have received the greatest attention (Broecker 1997; Taylor 1999; Clark *et al.* 2002). The upper level ocean currents flow northward in the Atlantic, carrying salty water that becomes progressively colder as it reaches the seas off Greenland and Norway. Sinking of this cold dense water in the North Atlantic, called North Atlantic Deep Water (NADW) formation, allows for a return southward flow at depth, and appears to be critical for the oceanic meridional overturning circulation (MOC). The formation of NADW is nonlinearly sensitive to surface density anomalies based on theoretical, observational and modelling studies, and may thus be highly susceptible to modulation by freshwater input. The nonlinearity is such that for some values of freshwater input to the North Atlantic, there are two stable states of the overturning circulation, which seems to exhibit hysteresis behaviour in response to freshwater changes (Rahmstorf 1995). The circulation could then potentially transit from one branch of the hysteresis loop to another with only a small perturbation to freshwater forcing if its initial state were near a transition point. As this oceanic circulation carries a great deal of heat, helping to give Western Europe a relatively warm climate for its latitude, this sensitivity makes the MOC a potential source of abrupt climate change.

Examples from Earth's history that allow testing of theory and models are the YD cold reversal and the 8.2 kyr event. These are the two primary sudden climate changes that have occurred since the Last Glacial Maximum. The cause of the YD is not clear, as geological evidence to support the prevailing theory, that passage of freshwater from a North American glacial lake to the North Atlantic caused a YD MOC slowdown, has not been found (Lowell *et al.* 2005). Such evidence is clear for the smaller 8.2 kyr event, however, as is corroborating evidence for a slowdown in the deep ocean circulation (Ellison *et al.* 2006). Recent modelling studies have matched the palaeoclimate records for multiple

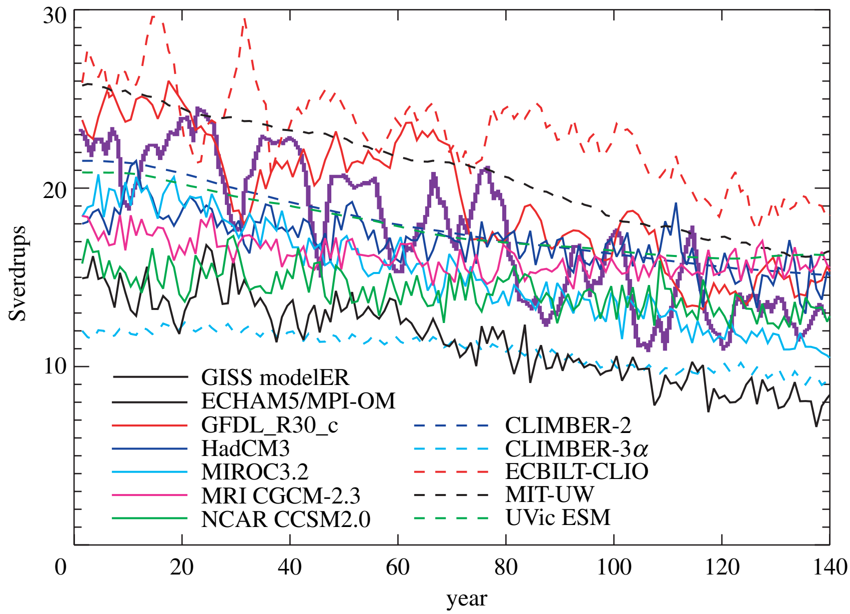

Figure 1. Change in maximum North Atlantic Ocean overturning circulation from a range of models. The vertical axis shows the strength of the overturning circulation in Sverdrup (Sv), while the horizontal shows the simulation year as CO_2 increases by 1%/year (a substantially faster rate of increase than projected under most future scenarios). Solid lines, results from GCMs; dashed lines, results from models of intermediate complexity. Adapted from Gregory *et al.* (2005). The solid grey line starting at approximately 23 Sv is the same Goddard Institute for Space Studies (GISS) model version that was able to reproduce the MOC response to the 8.2 kyr event (LeGrande *et al.* 2006), providing calibration as discussed in the text.

proxies, including oxygen isotopes, dust and methane, suggesting that current GCMs have a reasonable sensitivity to freshwater forcing (LeGrande *et al.* 2006). Given uncertainties in the magnitude and duration of the palaeo freshwater inputs, the sensitivity of GCMs could still be too small, but probably not dramatically so. There is strong evidence that as climate warms, precipitation at middle and high latitudes will increase due to the greater capacity of the atmosphere to hold water, which allows it to be transported further from its tropical source regions. This will deposit in the vicinity of 1 Sverdrup (Sv) year in additional freshwater over the twenty-first century according to model projections. In comparison, the 8.2 kyr event was probably triggered by a brief pulse of freshwater input more than an order of magnitude larger, leading to a slowdown in the MOC of approximately 40–60%. This suggests that the response over the twenty-first century is likely to be much smaller. Consistent with the inferences drawn from palaeoclimate data and modelling, GCMs and other types of models worldwide have investigated the potential slowdown of the MOC in the twenty-first century, and all find only fairly modest reductions (Gregory *et al.* 2005; figure 1). Thus, although ocean circulation changes are perhaps the most widely recognized source of potential abrupt climate change, modelling studies whose sensitivity is supported by comparisons with palaeoclimate data suggest that only a minor reduction in the MOC is probable during the twenty-first century. In all the GCMs, the effects of such a modest slowdown are outweighed by global warming, so that even in areas strongly affected by the strength of the MOC, temperatures increase (Gregory *et al.* 2005). Thus, a dramatic reduction in ocean circulation leading to sudden climate change in the near-term appears to be quite unlikely.

4. Ecosystem–climate interactions

Several mechanisms exist for potential feedbacks between climate change and biogeochemical systems. The relatively abrupt (decadal to century time scales) desertification of the Sahara *ca* 5500 years ago is an example in which such feedbacks are thought to have played a major role. Orbital forcing changes were very small during this period, and the desertification is thought to have taken place via climate–vegetation–dust feedbacks, perhaps with a role for human activities. The desertification marked the end of the African Humid Period, and both the onset and termination of this period occurred rapidly, and at similar thresholds in Northern Hemisphere (NH) summertime solar insolation (deMenocal *et al.* 2000). Coupled vegetation–climate models are progressing in their development, with initial results showing promising abilities to capture the relevant vegetation–albedo feedbacks. New processes are still being discussed, however (Knorr & Schnitzler 2006), and there are numerous issues relating to adequate simulation of the small scales important to vegetation in global models (Scheffer *et al.* 2005). Thus, it is not clear that models can at present reliably simulate these biogeochemical climate feedbacks. Additionally, the suitability of this example to modern conditions is not clear, however, as in most parts of the world human activities now dominate vegetation changes.

Biogeochemical cycles can also influence atmospheric GHG concentrations. One mechanism for this is modulation of CO_2 uptake by the terrestrial biosphere. If this were to saturate, it could lead to an abrupt increase in CO_2 forcing as more of the emitted carbon dioxide would remain in atmosphere (Woodwell 1992). Similarly, the oceanic CO_2 cycle could be affected by changes in nutrient deposition, with feedbacks on atmospheric abundance. As both the land and ocean CO_2 reservoirs are much larger than the atmospheric reservoir, small changes in either could substantially affect climate forcing. Again, however, our understanding of these processes and our ability to reliably project them into the future are still developing.

In addition to CO_2, changes in methane release from NH high-latitude peat bogs could cause substantial forcing. Molecule for molecule, methane is a more powerful GHG than CO_2. Methane, however, is relatively readily oxidized in the atmosphere, so that its lifetime is only about a decade. Since the lifetime of CO_2 is roughly a century, comparison of the effects of these gases depends on the length of time considered. The global warming potential of methane is approximately 20 times that of CO_2 over a century, and approximately 60 times that of CO_2 over 20 years. Alarmingly, a long-term study of a site in Sweden showed that permafrost and vegetation changes associated with warming temperatures have led to an increase in landscape scale CH_4 emissions in the range of 22–66% over the period from 1970 to 2000 (Christensen *et al.* 2004). This suggests that permafrost ecosystems with annual mean temperatures near the freezing point are indeed extremely sensitive to climate change. As peats contain vast reserves of methane, there is certainly the potential for abrupt climate change. This would require a sharp acceleration and expansion of methane release, but the transition across the freezing point provides a potential mechanism for such a shift. Again, however, our knowledge of how methane in peats might respond to climate change is quite limited by the paucity of both historical and modern data. Less dramatic, but still substantial changes to the global methane cycle could also arise from other feedbacks, such as the response of methane emissions from wetlands to climate change (Gedney *et al.* 2004; Shindell *et al.* 2004*b*) and of the methane sink, which will be affected by emissions changes as well as climate changes. The removal rate of methane could either increase or decrease depending on the emissions trajectory followed, making projection of future methane levels fairly uncertain.

5. Increased frequency of heatwaves

Events such as the 2003 heatwave in Europe have prompted much study of the influence of climate change on the probability for such extreme events to occur. Based on long European meteorological records, the probability of an event like the 2003 summer heatwave has been estimated to have doubled (from approx. 1 in 250 years) since the industrial revolution due to human impacts on climate, and is projected to increase to approximately one in two by approximately 2050 (Stott *et al.* 2004). This corresponds to slightly more than a doubling of the probability for severe heatwaves each decade between now and 2050. By the end of the century, summer temperatures such as those in 2003 would be considered normal (Beniston 2004) or even unusually cool (Stott *et al.* 2004) under climate projections assuming very limited controls on GHG emissions. As the temperature changes underlying these results are reasonably similar across models, the conclusions are likely to be at least qualitatively robust.

Data spanning most of the warming since the industrial revolution and covering most of the world's land area are consistent with these results, showing statistically significant decreases in the frequency of cold days and nights and increases in the occurrence of warm days and nights (Alexander *et al.* 2006). Also of concern are feedbacks involving atmospheric 'blocking' conditions in which relatively stable pressure systems remain located over a single area for prolonged periods. The frequency of these events may also increase as climate warms (Mickley *et al.* 2004). Such conditions not only augment heatwaves, but also allow large build-ups of pollutants that can lead to dangerously high levels of ozone (photochemical smog) and particulates. The heat and pollution can lead to substantial increases in premature mortality. Given the changes already apparent and projected, sudden climate change in summer extremes, under our definition of substantial changes during this century, seems highly probable.

6. Hydrologic cycle response to warming

Shifts in precipitation typically have even greater consequences than those in temperature, at least on time scales considered here, by affecting food production. Unfortunately, the extreme heterogeneity of precipitation in both space and time

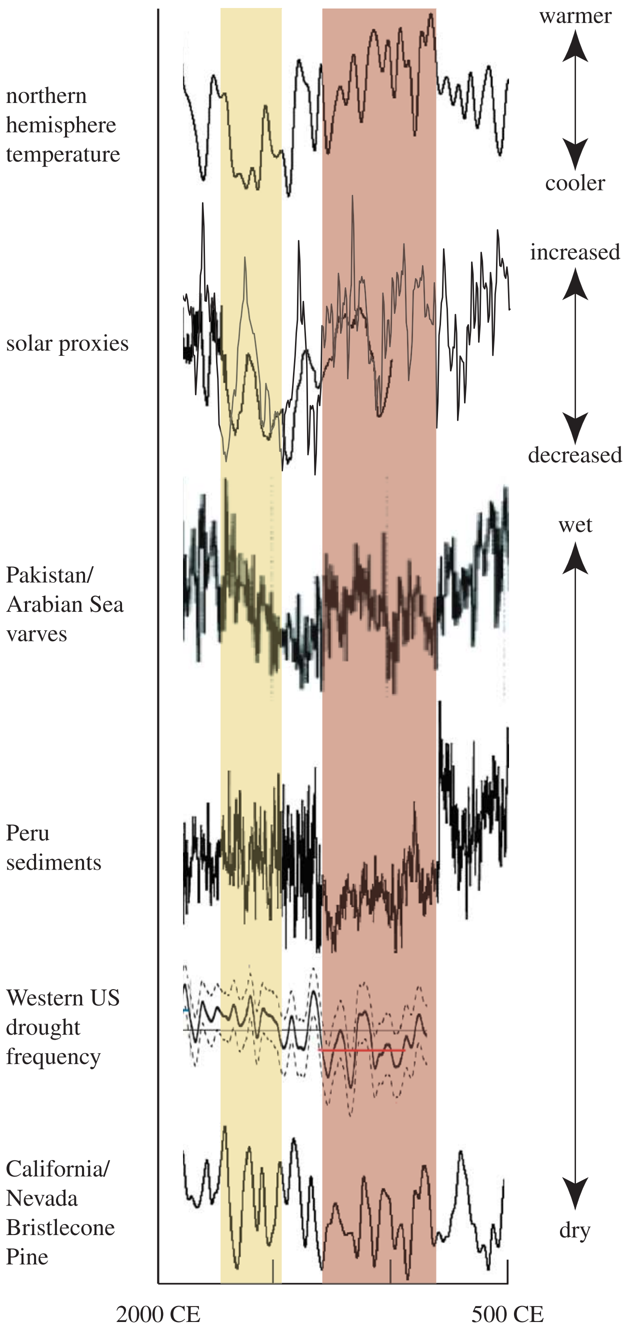

Figure 2. (*Caption opposite.*)

makes prediction of local scale changes extremely difficult. Projections of twenty-first century climate do show substantial modification of some large-scale aspects of the hydrologic cycle, however, including a drying of the subtropics and more precipitation at middle and high latitudes. This behaviour is consistent across

Figure 2. (*Opposite.*) Historical proxy data for temperature, solar output and the hydrologic cycle during the past 1500 years (prior to the industrial revolution). Temperature reconstructions are 40 year smoothed Northern Hemisphere results from a multiproxy analysis (Mann & Jones 2003). Solar proxies are the isotopes ^{10}Be from ice cores and ^{14}C from tree rings (Muscheler 2005) which indicate the strength of solar shielding of Earth from the cosmic rays that produce them (^{14}C is the atmospheric production rate inferred from the proxy data). The Arabian Sea varve (annually layered sediments) record is indicative of precipitation and river run-off from nearby Pakistan and the eastern Middle East (von Rad *et al.* 1999). Similarly, the ocean sediment record off Peru reflects precipitation in western central South America (Rein *et al.* 2004). The drought frequency in the western USA gives the percentage area subject to drought based on a wide network of tree-ring data (Cook *et al.* 2004). Finally, the Bristlecone Pine data show an especially long tree-ring record from the western USA (Hughes & Graumlich 2000). The shaded areas roughly indicate the times of the 'Little Ice Age' (yellow) and 'Medieval Climate Anomaly' (pink).

many climate models and rests on fundamental physical principles (Mitas & Clement 2006; Held & Soden in press). It is thus inherently more reliable than small-scale changes. Briefly, boundary layer moisture increases in response to positive radiative forcing as a result of surface warming, the maintenance of near-constant relative humidity, and the exponential Clausius–Clapeyron law governing the holding capacity of atmospheric water vapour. The circulation that carries water out of the arid subtropics will thus export more water roughly following the increase in boundary layer moisture. Conservation of water requires that this flux be equal to evaporation minus precipitation in any given region (the net input of water). While positive radiative forcings lead to increased evaporation and a slowdown of the tropical overturning circulation, these are not adequate to balance the increase in the holding capacity of the atmosphere. Hence precipitation must decrease in the subtropics, with compensating precipitation increases along the equator and at middle and high latitudes to maintain moisture balance in those regions.

As with changes in ocean circulation, the Earth's history provides examples against which to test our models and our understanding of how external forcings affect the hydrologic cycle. This is especially important in the case of precipitation responses, where results from analysis of modern data have been ambiguous (Chen *et al.* 2002; Mitas & Clement 2005, 2006). Historical data spanning the past millennium show substantial variations in aridity in the dry bands of the subtropics (figure 2). As the figure shows, palaeoclimate records from a variety of sources and subtropical locations suggest that the Medieval period was generally marked by drier conditions, including prolonged droughts, which became less prevalent during the so-called 'Little Ice Age'. These records are supported by additional sediment and lake level records, including some showing wetter conditions near the equator, as well as fire residue and cultural records (Hodell *et al.* 2001; Haug *et al.* 2003; Cook *et al.* 2004; Rein *et al.* 2004). The changes have been linked to variations in solar luminosity, as shown in the figure. Solar proxy data suggest generally increased output during the Medieval period and reductions during the Little Ice Age, though the magnitude of the change is difficult to quantify. Thus, there is substantial evidence linking solar variations during the past millennium to tropical/subtropical hydrology and climate. A clear solar–hydrological cycle relationship is less obvious during the previous millennium, when solar changes also do not correlate as clearly with surface temperature.

Furthermore, some parts of the globe show much more complex behaviour even during the past millennium. For example, tropical African records indicate drier conditions with increasing irradiance in lakes to the far east (Naivasha, Victoria; Verschuren *et al.* 2000; Stager *et al.* 2005) but wetter conditions in lakes just to the west (Tanganyika, Edward; Alin & Cohen 2003; Russell & Johnson 2005). Thus, many aspects of past climate variability are clearly not yet fully understood.

A recent study with the NASA Goddard Institute for Space Studies (GISS) climate model has shown that a coupled ocean–atmosphere climate model incorporating the response of atmospheric ozone to solar irradiance changes can reproduce the pattern apparent in historical records, with a drying of the subtropics and an increase in precipitation along the equator in response to irradiance increases (Shindell *et al.* 2006*b*). The agreement between the historical record and the simulation in the general pattern of a wetter tropics and drier subtropics in response to solar forcing is an important validation of the physical mechanism underlying the occurrence of this same pattern in model simulations of the response to projected increases in GHGs.

By comparing the response to both climate forcings in the same climate model, we can see the similarities quite clearly (figure 3). In these experiments, the solar simulations were driven by a change in solar output equivalent to the difference between solar maximum and minimum over the approximately 11-year cycle as measured by satellites (approx. $0.19\ \mathrm{W\,m^{-2}}$ instantaneous radiative forcing at the tropopause, equivalent to $1.1\ \mathrm{W\,m^{-2}}$ change in solar output, approx. 0.1%). The change includes the spectral variations of the solar output, which varies much more in the higher energy ultraviolet, affecting ozone, than in the visible. The magnitude of this forcing is a mid-range estimate for longer-term solar variations, and is in good agreement with recent estimates based on solar physics models (Wang *et al.* 2005*b*). The results analysed here are averages over 70 years of model. Future projections are taken from GISS simulations performed for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). These experiments were driven by long-lived GHG (CO_2, CH_4, N_2O and CFC/HFCs) changes following the A1B emission scenario, again a mid-range estimate. The results presented here are trends calculated over the first and second halves of the twenty-first century from an ensemble of five climate model runs, and are similar to those seen in other GCMs (Mitas & Clement 2006; Held & Soden in press).

The zonal average response matches very closely in the two experiments. Both show substantial increases in precipitation along the tropical rain belt, with decreases to both sides in the subtropical desert bands. The higher latitudes show increases, as noted in the discussion of the oceanic circulation response to climate change. The subtropical precipitation decreases are statistically significant in both hemispheres in the solar case, and in the Northern Hemisphere subtropics for the 50-year GHG trends. The full 100-year SH subtropical trends are also significant. Impacts from the drying of the NH subtropics, which reach approximately 15% over the twenty-first century, are likely to be especially pronounced. The precipitation changes within this band are highlighted for two semi-arid regions: the southwestern US/Mexico, and the Mediterranean/Middle East. The changes are especially large for the SW US/Mexico, where the regional mean decrease is nearly $100\ \mathrm{mm\,yr^{-1}}$ over the twenty-first century. As the changes result from well-understood large-scale features of the atmosphere (the tropical overturning circulation and atmospheric moisture balance), they are reliable in global models even though these models have difficulty simulating local precipitation. In examining the distribution of magnitudes of precipitation changes within these regions, we therefore show a histogram of changes without attributing these to individual model grid boxes (figure 4). These show that a substantial portion of the SW US/Mexico region experiences a decreased precipitation of greater than 60 mm yr^{-1} (approx. 7%) in each 50-year future interval (with a few model grid boxes showing greater than 100 mm yr^{-1} (approx. 10%) decreases). Similarly, the distribution is fairly broad over the Mediterranean/Middle East, with a substantial area exhibiting precipitation decreases of greater than 40 mm yr^{-1} (approx. 17%) in each 50-year interval.

While most of these changes are due to altered tropical overturning circulation and moisture balance, those in the Mediterranean and Middle East also reflect the systematic response of the North Atlantic Oscillation (NAO) or Arctic Oscillation (AO) to increasing GHGs. This internal variability mode shifts towards its positive phase in the GISS GCM used in the simulations described earlier and in most climate models (Miller *et al.* 2006), leading to a greater prevalence of winter Atlantic storms following the more northerly storm track towards Britain and Scandinavia and to a reduction along the southerly track leading to the Mediterranean (Hurrell 1995; Quadrelli *et al.* 2001). As with the tropical circulation shifts, these results also have support from comparison with historical shifts in the NAO/AO in response to solar (Shindell *et al.* 2001) and volcanic (Collins 2003; Shindell *et al.* 2004*a*) forcing. Thus, the systematic positive shift seen in GCMs brings wetter conditions to north Europe, and drier conditions to the Mediterranean and Middle East regions. Based on the difference between the response in this region relative to other NH subtropical areas, the shift in extratropical circulation is responsible for roughly one-third of the changes seen there (mostly during winter), the rest being driven by the changes in tropical circulation and moisture. Since both the above effects on precipitation result from the response of large-scale patterns to a warming climate, and such responses can be captured by global models, these simulated changes inspire greater confidence than general GCM projections of regional precipitation response to climate forcing.

Note that the AR4 simulations did not include the aerosol indirect effect which suppresses rainfall by making a greater number of smaller cloud droplets. As emissions from the developing world are projected to increase rapidly over coming decades, this may, at least in the short term, further inhibit precipitation in the subtropics. Over the longer term, direct anthropogenic emissions of aerosol pollutants are expected to decrease owing to projected efforts to improve human health. However, aerosol emissions can also be affected indirectly by humans. For example, dust emissions and biomass burning emissions, which generate many aerosol species, are both influenced by land use and climate change. These effects are difficult to project reliably. Should the net effect be a decrease in future aerosol emissions, this could offer a potential route to at least partially offset some of the projected drying of the subtropics.

The effects of the water stress induced by these precipitation changes and the resulting increased drought frequency in historical times appear to have been substantial, with civilizations abandoning cities and shifting to new areas despite

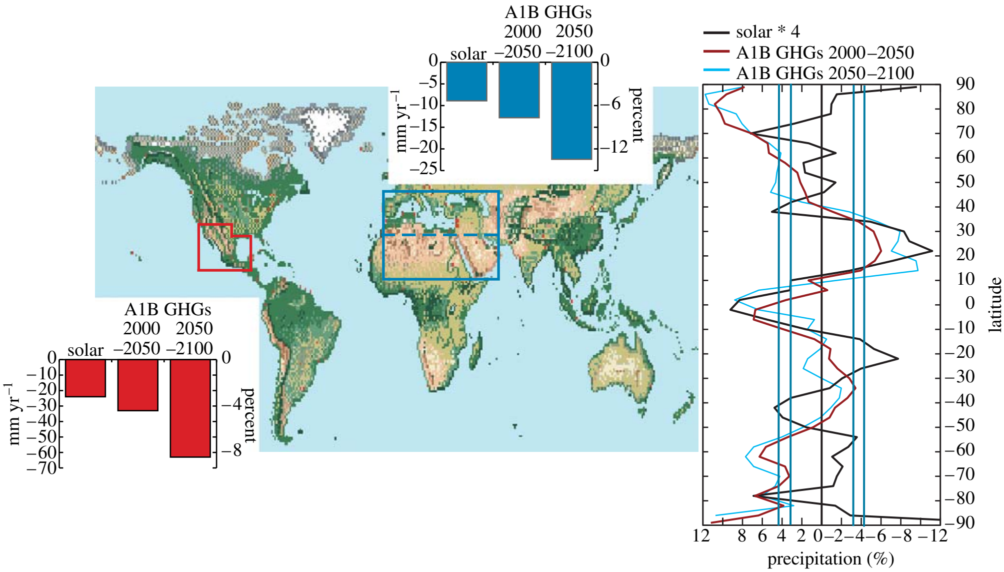

Figure 3. Precipitation changes in response to solar and GHG forcings. Solar results are the long-term equilibrium response to increased irradiance, while the GHG results are 50-year trends in ensemble simulations driven by the A1B mid-range scenario (see text for details). Regions are defined as the land area within the boundaries shown above: SW US and Mexico (red, 16–36° N; 85–125° W; excluding 28–36° N and 85–100° W) and Mediterranean/Middle East (blue, 12–40° N; 10° W–65° E). A narrower Mediterranean/Middle East region (28–40° N, 10° W–65° E, dashed line gives southern boundary) was also analysed, and shows larger precipitation decreases for the A1B simulations ($-22\ \mathrm{mm\ yr^{-1}}$ 2000–2050 and $-34\ \mathrm{mm\ yr^{-1}}$ 2050–2100, which are similar in percentage terms), but smaller changes in response to solar forcing. The right-hand graph shows the zonal mean changes aligned with the map on the left, highlighting the increased precipitation along the equator and decreases in both subtropical arid bands. The blue vertical lines indicate the 95% confidence level from approximately 75° S to 70° N in the simulations (outer lines near 4% are for solar simulations, inner lines near 3% are for the GHG ensemble; note that the subtropical drying is highly significant in the total 2000–2100 A1B GHG trend). The zonal mean response in the solar simulation has been multiplied by 4 to fit on the same scale as the GHG simulations.

the substantial loss of investment it entailed (deMenocal 2001; Hodell *et al.* 2001; Haug *et al.* 2003). It has been speculated that climate change played a role in historical events such as the collapse of the Maya, the abandonment of the cities of the Ancestral Puebloans in the SW US and migrations of the Moche in what is now Peru. Similarly, North Africa and the Middle East have suffered from periods of extensive drought (deMenocal 2001) while societies dependent upon rainfall from the Indian and Asian monsoons, such as the Angkor civilization, could have been severely stressed by changes associated with past solar variability (Fleitmann *et al.* 2003; Wang *et al.* 2005*a*).

Climate change probably operated in concert with other factors, including land use, social upheavals and political transformations, to cause major disruptions (Diamond 1994). While modern societies possess greatly advanced technology for monitoring and adaptation, they also compound the effects of water stress through their vastly increased demand. A case in point is the recent shrinkage of Lake Chad in northern Africa. This lake appears to have been

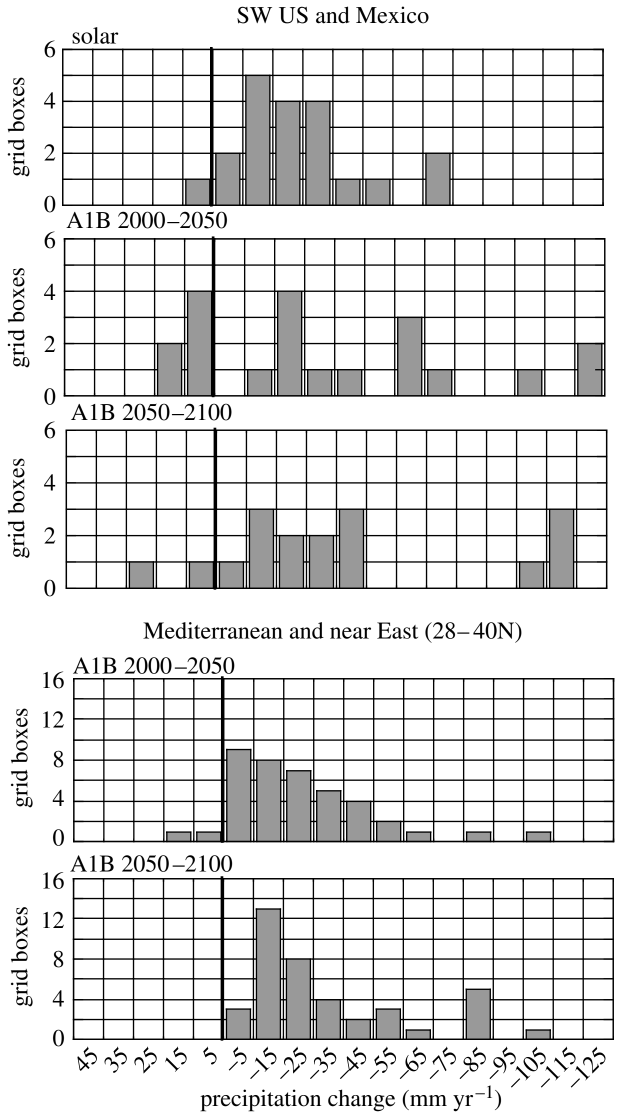

Figure 4. Distribution of magnitudes of precipitation changes in response to solar and GHG forcings. The histograms show the values throughout the regions shown in figure 1, using the narrow version of the Mediterranean/Middle East region (dashed in figure 1). Precipitation changes are given in 10 mm yr^{-1} intervals, with the axis label indicating the centre. Simulations are the same as in figure 1. The SW US/Mexico response to A1B GHGs for 2050–2100 also has one value off the above chart for a box near the Yucutan, with a precipitation decrease of 300 mm d^{-1}. Model grid boxes of 4° by 5° cover roughly 350 by 400 km at these latitudes.

substantially larger through most of the Holocene than it is at present. As less precipitation falls in the subtropics, the many farmers living in the area must draw more water from the lake for their crops. Hence, not only does the lake receive less input from rain, but also more is taken out since the area now has a sizeable population. Once the world's sixth largest lake, it has dwindled to one-tenth its former size during the last 40 years. Thus, the effects of subtropical drying trends may perhaps be already upon us, and the future projections (figure 3) certainly qualify as substantial changes within the next century.

7. Ice sheet decay and Arctic warming

One of the most worrisome potential consequences of global warming is melting of the polar ice sheets. As noted earlier, ice sheet decay appears to take place much more rapidly than ice sheet growth, but the question remains as to just how quickly ice sheets can respond to rapid warming. Recent signs from Greenland suggest that the response time may in fact be centuries rather than millennia usually associated with ice sheet processes. The melt area on Greenland has been increasing rapidly, with a trend of 0.7%/year from 1979 to 2002 and a record melt extent of 690 000 km^2 in 2002 in comparison with an average of 455 000 km^2 from 1979 to 2003 (Steffen *et al.* 2004). This previous record was exceeded in 2005. Areas with most rapid melting show thinning of 70 m in 5 years.

The mass balance of the ice sheet is determined by the difference between accumulation, primarily atop the sheet and losses that are largely from the edges. Recent data indicate that a portion of the increased loss has been offset by increased accumulation at the highest parts of the ice sheet towards the centre (Luthcke *et al.* 2006; perhaps due to the increased water exported from the subtropics to higher latitudes discussed previously). However, the melt elevation is increasing and now extends up to 2000 m. Melting at high altitudes induces a positive feedback since as melt occurs, elevation decreases, hence the surface descends to lower altitudes where temperatures are warmer. Of further concern is that the discharge from major ice streams is also increasing rapidly, with as much as a doubling of the annual mass loss from Greenland during the past decade, with estimates of the annual loss ranging from 80 to 220 km^3 (Krabill *et al.* 2004; Velicogna & Wahr 2005; Luthcke *et al.* 2006; Rignot & Kanagaratnam 2006). Acceleration of land ice after the collapse of the buttressing Larsen B ice shelf on the Antarctic Peninsula also indicates a rapid response. While the build-up of ice sheets requires snowfall over millennia, melting is a 'wet' process with positive feedbacks such as surface meltwater descending to bedrock at the base of the ice sheet and lubricating its flow (Zwally *et al.* 2002). Thus, a multitude of data point to the existence of several positive feedbacks and relatively rapid ice sheet decay processes. This is worrisome as there is enough water locked in Greenland to raise the sea level by 7 m worldwide. During the last interglacial *ca* 130 000 years ago, melting of Greenland contributed approximately 2–3 m of sea-level rise (with a total increase in sea level estimated at 4–6 m). Since the temperature during that period was only a degree or so warmer than the present temperature, this suggests that substantial melting is indeed probable with the temperatures expected during this century. Though the main effects on sea level may not be felt this century, they may however be 'locked in' by the warming that is projected to take place. The uncertain, but potentially quite large, sea-level changes due to melting land ice will add to the well-understood increase owing to thermal expansion, which may be as large as 20–30 cm by 2100 (Meehl *et al.* 2005).

Arctic sea ice changes will also affect Greenland's climate and the broader circum-Arctic region via albedo (reflectivity) changes. The summer extent of Arctic sea ice has decreased by about one-fourth over the past 30 years (Stroeve *et al.* 2005), and observations also suggest a substantial reduction in the sea ice thickness (Rothrock *et al.* 1999). A part of the loss is related to increased westerly wind speeds associated with the NAO/AO, which enhance the breakup and export of ice from the Arctic Ocean. As noted previously, the gradual strengthening of these winds over the past several decades has been linked to the build-up of GHGs in the atmosphere (Miller *et al.* 2006). A part of the polar amplification of warming is related to the ice–albedo feedback that operates at high latitudes, with other influential factors including atmospheric aerosols (Lubin & Vogelmann 2006), tropospheric ozone (Shindell *et al.* 2006*a*) and the deposition of aerosols on ice (Koch & Hansen 2005). Thus, several positive feedbacks and forcings may be at work in the decline of Arctic sea ice and Arctic snow cover. Both decreases lead to reduced reflection of incoming solar radiation, and hence to Arctic warming, which may exacerbate the melting of Greenland.

The circum-Arctic in turn can respond to polar warming with vegetation changes, which make the planet darker and hence augment the warming further (Chapin *et al.* 2005). Large changes are already being observed in places such as Alaska, where forest ecosystems are undergoing rapid change and permafrost is melting dramatically. The retreat of snow and ice cover can have dramatic effects for species such as polar bears that depend on ice cover near shore to reach their food supply. High-elevation ecosystems worldwide are similarly vulnerable to changes in climate as they have no cooler places to which they can migrate. While human population in the Arctic and at very high altitudes may be relatively small, for the people and other living things there it is probably justified to say that sudden climate change is already underway.

The Antarctic ice sheet has shown less dramatic changes in recent years. This is partially due to cooling temperature trends over much of the continental interior (Schneider & Steig 2002). These trends have been linked to both ozone depletion (Kindem & Christiansen 2001) and increasing GHGs (Kushner *et al.* 2001) largely via modulation of the Southern Annular Mode, a natural variability pattern involving the strength of the circumpolar westerlies akin to the AO. As the westerlies strengthen, Antarctica is increasingly isolated and hence colder. The projected recovery of ozone is expected to oppose further strengthening of the westerlies, however, allowing the general greenhouse warming to extend to Antarctica over the coming decades (Shindell & Schmidt 2004). Additionally, a major portion of the Antarctic ice sheet, the West Antarctic Ice Sheet (WAIS), is grounded largely below sea level and is thus highly susceptible to rapid melting by heat loss to invading seawater. Melting of the entire WAIS would raise global sea levels by 6 m. The far larger East Antarctic Ice Sheet (with 50 m sea-level equivalent of water) is fortunately grounded mostly on land, and seems to be more stable. The WAIS may have recently begun to lose mass, with recent data showing loss rates of 152 ± 80 km^3 ice per year for Antarctica, with most of the loss coming from the WAIS (Velicogna & Wahr 2006). Thus, increased melting of Antarctic ice is a distinct possibility.

The consequences of large increases in sea level would be disastrous. Many major cities of the world are at low elevation, so that for a sea-level rise of 2 m, roughly 60 million would be displaced in Calcutta and approximately 40 million in Shanghai.

Large areas of Bangladesh, south Florida and New York City, for example, would be under water. A rise of 6 m would affect more than 90 million in China, approximately 70 million in India, Bangladesh and Sri Lanka, more than 25 million in Western Europe (especially the Low Countries) and approximately 10 million in the USA. Thus, the potential for massive societal impacts from melting of Greenland or the WAIS is clear. Predicting the timing of such melting is highly uncertain, but recent observations indicating faster than expected ice sheet response and rapid acceleration of melting are very worrisome. Hopefully, such an outcome can be averted. However, it seems clear from historical precedent that we will pass a threshold for substantial (at least 2–3 m sea level) melting during this century, so that the next 100 years could mark a commitment to future sudden climate change by pushing the ice sheets towards destabilization.

8. Conclusions

Palaeoclimate data clearly reveal that sudden climate changes have happened in the past, often with much smaller changes in radiative forcing than those of the twentieth and twenty-first centuries. However, specific triggers for these palaeoclimate events may have developed over long periods, such as the glacial lakes formed behind slowly retreating ice sheets. Nevertheless, historical evidence provides crucial tests of our models and our understanding of sudden climate change. For example, validations of the oceanic response to freshwater forcing against historical events give us confidence in model projections showing only a modest twenty-first century change in Atlantic Ocean circulation.

Some sources of historical sudden climate change, such as asteroid impacts or super-volcano eruptions, appear to be improbable in the coming century based on past climate records. Massive methane release by hydrates or from peats also seems to have been extremely rare in the past, but could become more probable in the future world under the influence of anthropogenic forcing. However, at present, it is not possible to judge the probability for such changes reliably.

Melting of the polar ice sheets is perhaps the gravest probable consequence of climate change over the coming 500 years. Impacts during the next 100 years are difficult to assess, but at minimum, the risk of catastrophic sea-level rise may be greatly influenced by the trajectory of anthropogenic climate forcing. The assessment presented here indicates that during the next century, changes in the hydrologic cycle, influencing precipitation and drought, and in the frequency of summer heatwaves are likely to have the most profound effects. The projected drying of the subtropics is likely to be one of the most severe near-term consequences of climate change, as these areas are already water stresses in many cases and their population, and hence water demand, has been increasing rapidly.

As mentioned in §1, sudden climate change is inherently more likely to capture media and public attention, and hence influence policy. This raises the intriguing possibility for climate–socio-economic feedbacks. In such a scenario, an early onset of more frequent summer heatwaves or increased droughts in the SW US and Mexico region and/or in the Mediterranean and Middle East could prompt a dramatic increase in the world's readiness to mitigate climate change. They might have a substantial impact on the likelihood of the worst longer-term changes, such as devastating sea-level rise, coming to pass. It would be tragic, however, if the world waits to act forcefully, either until sudden climate change is upon us or until the long-term consequences are better appreciated, only to find that it is too late to avert most of the damage. Such a possibility is all too real, given the rapid pace of climate change and the comparatively slow pace of emission reduction policies.

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